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ANNUAL STATUS REPORT

For NASA Grant # NAG 3-1490

Title of the Grant:

"Investigation of the Basic Physics of High Efficiency Semiconductor Hot Carrier Solar Cell"

P. 17

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Period Covered:

05/31/94---05/30/95

This annual report will include: I. Research accomplishments: II. Publications, abstracts and Ph.D theses; and III. Continuing research plan for the third year.

I. RESEARCH ACCOMPLISHMENTS

The main purpose of the proposed research program for grant # NAG 3-1490 is to investigate potential semiconductor materials and their multi-band-gap MQW structures for high efficiency solar cells for aero space and commercial applications.

During the past two years, significant progress on the proposed research program was made. We have obtained samples of epitaxial layers of InP, GaInP, InGaAs, and InGaAsP, and single-and-multiple quantum wells (QW and MQW) of InGaAsP/InP from Epitaxial Products Inc., University of Illinois, and the AT&T Bell Labs. The absorption and PL spectra, the carrier dynamics and band structures have been investigated for semiconductors of InP, GaP, GaInP and InGaAsP/InP MQW structures, and for semiconductors of GaAs and AlGaAs by our previous measurements. The barrier potential design criteria for achieving maximum energy conversion efficiency, and the resonant tunneling time as a function of barrier width in high efficiency MQW solar cell structures have also been investigated in the first two years.

(NASA-CR-198945) INVESTIGATION OF THE BASIC PHYSICS OF HIGH EFFICIENCY SEMICONDUCTOR HOT CARRIER SOLAR CELL Annual Status Report, 31 May 1994 - 30 May 1995 (City Coll. of the City Univ. of New York) 17 p

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The samples we have obtained (or will obtain) for the research of the grant # NAG 3-1490, and the sample makers (companies) are described in the following table:

<u>Samples</u>	Types	Companies	<u>Status</u>
InP	bulk	Epitaxial Products Inc.	obtained
GaP	bulk	Brian Fitzpatrick	obtained
GaInP	bulk	Epitaxial Products Inc.	obtained
InGaAs	bulk	Epitaxial Products Inc.	obtained
InGaAsP	bulk	Epitaxial Products Inc.	obtained
InAlGaP	QW	University of Illinois	obtained
InAlGaP	MQW	University of Illinois	obtained
InGaAsP/InP	bulk	AT&T	obtained
InGaAsP/InP	MQW	AT&T	obtained
GaAs/AlGaAs	MQW	Grumman and/or CCNY	to be obtained
InGaAs/InP	MQW	AT&T	to be obtained

For the past year, we have designed an InAs/InGaAs-InGaAs/GaAs-GaAs/AlGaAs MQW solar cell structure based on our measurements on GaAs and AlGaAs, and our calculations on barrier potential design criteria in multi-band-gap MQW solar cell structures for the purpose of achieving maximum energy conversion efficiency. Based on our measurements on bulk and MQW semiconductors of InP, GaInP and InGaAsP/InP, and our calculations on barrier potential design criteria, an InP-based InAs/InGaAs-InGaAs/InP-InP/GaInP multi-band-gap MQW solar cell structure have being calculated. We have obtained six InGaAs/InP bulk and MQW samples from the Solid State Technology Center of the AT&T Bell Labs, and have measured the absorption and PL spectra for these samples at room temperature and 77 K. We have also measured the time-resolved IR absorption spectra in InGaAsP/InP MQWs and the time evolution of the change of the hot electron population in InGaP and the temperature dependence of hot carrier dynamics in GaAs. A number of research results under the support of the NASA grant # NAG 3-1490 have been published in scientific journals and presented at conferences.

The following highlights the progress accomplished during the past year:

I.1. Design of the InAs/InGaAs-InGaAs/GaAs-GaAs/AlGaAs MQW solar cell structures for high efficiency solar cells

Based on our previous carrier dynamics measurements and the time-dependent short circuit current density calculations, we have designed an InAs/InGaAs-InGaAs/GaAs-GaAs/AlGaAs MQW solar cell structure with 15 band gaps as shown in Fig.1.

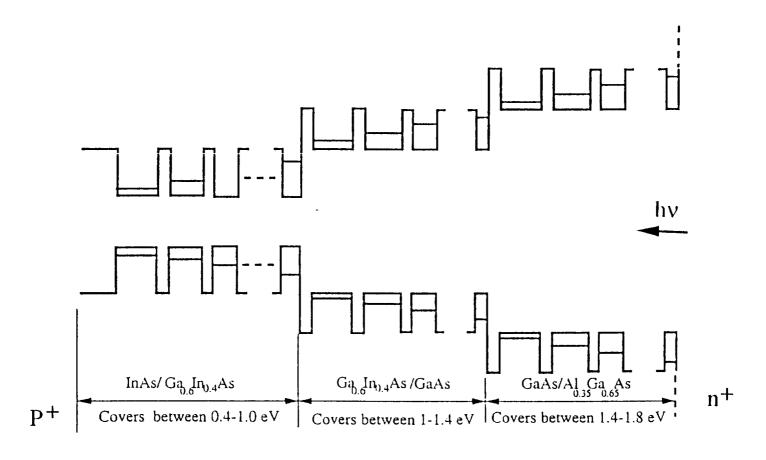


Fig.1. Schematic diagram of an InAs/InGaAs-InGaAs/GaAs-GaAs/AlGaAs MQW solar cell structure with 15 band gaps changing from 0.4 eV to 1.8 eV. Under the resonant condition, energy levels will couple together and carrier collection will be achieved via resonant tunneling.

The quantum wells are designed under flat band conditions such that the effective absorption band-gap will cover the energy spectrum of interest. To insure maximum energy level coupling throughout the structure under the application of electric field, the quantum well widths are designed such that the bound states lie at an energy equal to the voltage drop between adjacent wells. Carriers absorbed in the MQW region will tunnel through the leftmost structures and then collected between n⁺ and p⁺ collector sides (see Fig.1) through resonant tunneling.

Based on our calculations of the time-dependent short circuit current density at the collector side of the MQW solar cell structures using the time-dependent Schrodinger equation and the relation between the output voltage at the maximum power and the barrier potential, it was shown that for MQW based solar cell structures made with a small quantum well material band gap, such that of InAs in InAs/GaInAs structures, the efficiency peaks at a barrier potential of about 450 meV as

shown in Fig.2. For structures of a large quantum well band gap, such that of GaAs in GaAs/AlGaAs, the efficiency declines linearly as the barrier potential is increased (see Fig.2). For the optimum condition of energy conversion efficiency, we usually choose 300 meV as a barrier potential for structures with higher band gaps.

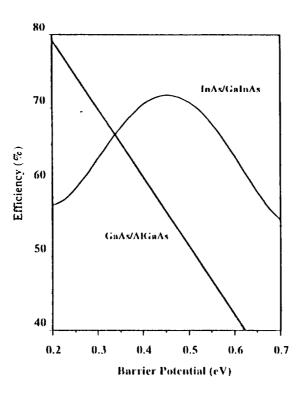


Fig.2. The calculated energy efficiency of $InAs/Ga_XIn_{1-X}As$ and $GaAs/Al_XGa_{1-X}As$ MQW structure based solar cells as a function of barrier potential.

The designed multi-band-gap MQW solar cell structures consist of three basic unit MQW structures: InAs/GaInAs, GaInAs/GaAs and GaAs/AlGaAs. The effective band gaps vary gradually from 0.4 eV to 1.8 eV by 15 steps. As shown in the research proposal for the third year continuation for Grant # NAG 3-1490, the energy conversion efficiency for a three- band-gap tandem system can reach ~56 %, and the efficiency for a 36-band-gap tandem system can reach ~72%. The efficiency for the designed InAs/InGaAs-InGaAs/GaAs-GaAs/AlGaAs MQW system having 15 band gaps is expected to reach ~65%.

The first basic unit structure consisting of InAs/Ga_{0.6}In_{0.4}As multiple quantum wells as shown in Fig.3, has the barrier potential of 450 meV which corresponds the efficiency peak. Well widths change from 200 A to 58 A so that the effective band gaps---the energy difference between the first hole and electron levels--- will change from 0.4 eV (the band gap for well material of

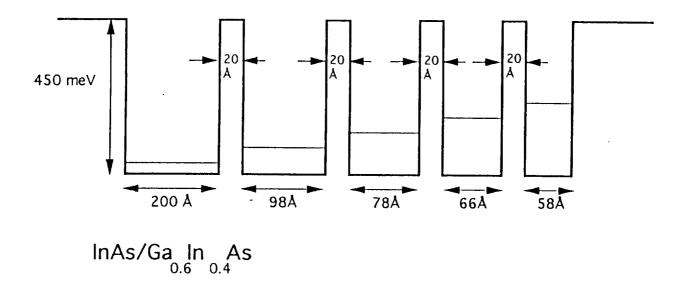


Fig.3. Schematic diagram of an InAs/Ga_{0.6}In_{0.4}As MQW structure with well widths changing from 200 A to 58 A, and effective band gaps varying in the energy range from 0.4 eV to 1.0 eV.

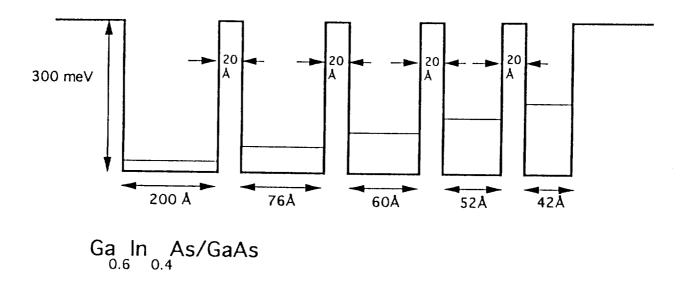


Fig.4. Schematic diagram of a $Ga_{0.6}In_{0.4}As/GaAs$ MQW structure with well widths changing from 200 A to 42 A, and effective band gaps changing in the energy range from 1.0 eV to 1.4 eV.

InAs) to $1.0\,\mathrm{eV}$ (the band gap for barrier material of $Ga_{0.6}In_{0.4}As$) and match the resonant tunneling conditions under the application of the electric field. Each well-barrier unit structure will be repeated to increase the thickness to the effective absorption length within appropriate spectral range.

The InAs/Ga0.61n0.4As MQW structure is followed by a MQW structure of Ga0.6In0.4As/GaAs with a wider energy band gap, as shown in Fig.4, so that a wider range of the solar spectrum can be covered. The barrier potential is chosen to be 300 meV to meet the efficiency peak. The well width varies from 200 A to 42 A to form multiple effective band gaps, which change in the energy range from 1.0 eV to 1.4 eV, and match the resonant tunneling condition.

The third basic unit consists of GaAs/Al_{0.35}Ga_{0.65}As MQW with effective band gaps varying in the energy range from 1.4 eV to 1.8 eV as shown in Fig.5, which is wider than that for Ga_{0.6}In_{0.4}As/GaAs. The barrier energy is chosen to be 300 meV to match the efficiency peak. The well width varies from 200 A to 41 A to meet the resonant tunneling conditions.

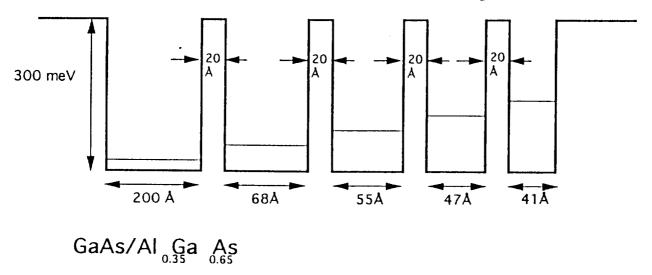


Fig.5. Schematic diagram of a GaAs/Al_{0.35}Ga_{0.65}As MQW structure with well widths changing from 200 A to 41 A, and band gaps changing in the energy range from 1.4 eV to 1.8 eV.

These three basic unit structures would be characterized using absorption-and-PL spectroscopy and yield measurements. The spectra would be compared to determine if transfer is produced. The combined system using these three multi-band-gap MQW structures of InAs/GaInAs, GaInAs/GaAs and GaAs/AlGaAs is shown in Fig.1. As mentioned above, it has 15 effective band gaps varying gradually in the energy range from 0.4 eV to 1.8 eV, and its

energy conversion efficiency is expected to reach ~65%. If realized, this will address the high efficiency solar cell energy converters to the marketable.

I.2. Absorption and PL measurements in InGaAsP/InP MQW structures

InGaAsP/InP MQW structures will be one of the basic unit for the InP-based multi-band-gap MQW structures for solar cells and other devices. We have obtained six InGaAsP/InP MQW samples from Dr. Reynolds and Dr. Swaminathan in the Solid State Center of the AT&T Labs at Breinigsvill. The layer diagram of one of the InGaAsP/InP MQW samples is shown in Fig.6. The MQW structures consist of 9x8 periods of 70 A InGaAsP wells and 100 A InP barriers.

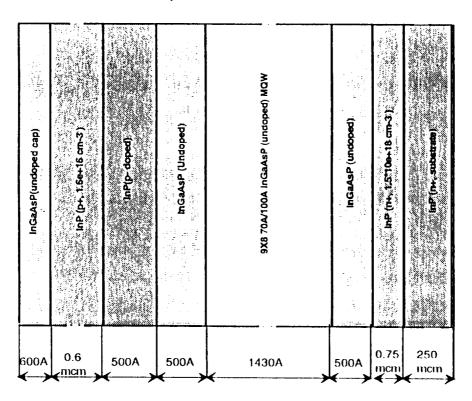


Fig.6. Schematic diagram for the layer structure of InGaAsP/InP MQW samples.

The absorption and PL spectra in InGaAsP/InP bulk and MQW structures have been measured at room temperature and 77 K with different pump wavelength and pump intensity. As an example, the energy band structure for an InGaAsP/InP MQW sample with the well width of 70 A and the barrier width of 100 A is shown in Fig.7. The measured PL spectrum at room temperature with 532 nm pump, and the excitation intensity dependence of the PL spectra for this 70 A MQW samples are shown in Figs.8 & 9, respectively.

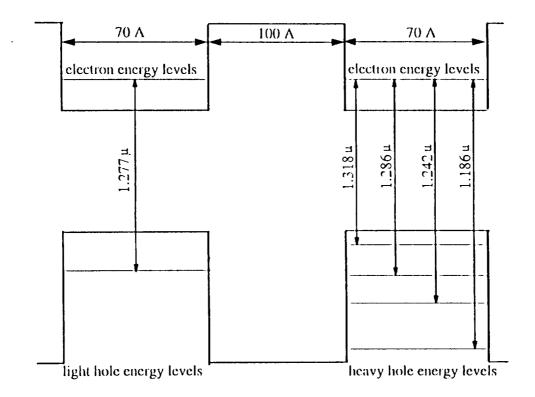


Fig.7 Energy band diagram of InGaAsP/InP MQW structure samples.

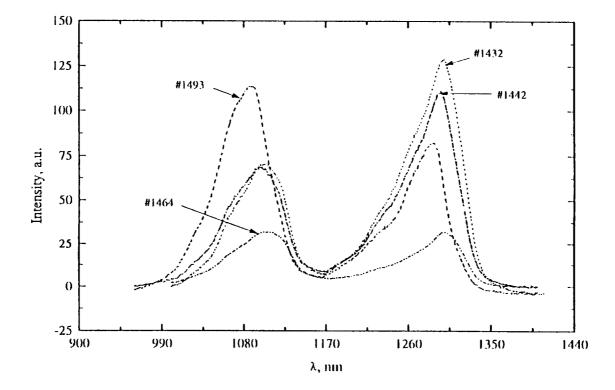


Fig. 8 Measured PL spectrum for an InGaAsP/InP MQW structure at room temperature. Samples of #1432, #1442, #1464 and #1493 differ in dopant level of p^+ InP clad layer.

The first peak at the longer wavelength of 1.30 μm is expected and formed by the recombination transitions of ground state electrons and holes. While the second PL peak at 1.11 μm is, in comparison with the PL spectrum for bulk InGaAsP/InP layers, attributed to the transition from the first above-barrier electron resonant state. The calculated result using physical model of above-barrier resonant states is in a good agreement with the measured value. The existence of these resonant states may affect InGaAsP/InP solar cell activities.

To further investigate the effect of above-barrier resonant states on the spectroscopy and carrier dynamics, we have designed another three InGaAsP/InP MQW samples with same well width and different barrier width (70A/70A, 70A/100A, and 70A/150A), which have recently been fabricated by AT&T Labs in Breinigsvill. We have started to measure the absorption and PL spectra for these new samples.

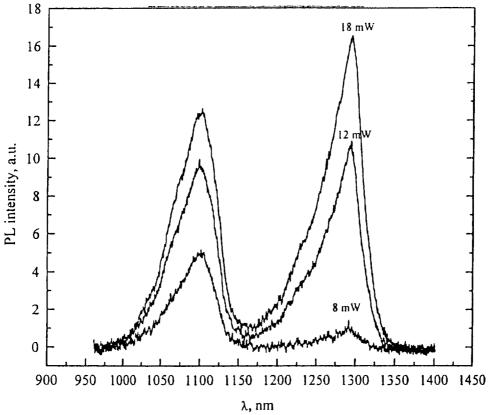


Fig.9. Pump intensity dependence of PL spectra for an InGaAsP/InP MQW structure.

I.3. Time-resolved IR absorption measurements in InGaAsP/InP MQW structures

Time-resolved IR absorption for InGaAsP/InP bulk and MQW structures has been measured by femtosecond visible-pump and IR-probe absorption spectroscopy. The transition time of hot electrons from the excited states to the ground state in the well was measured to be shorter than 700 fs which is indicated by the rise portion of the measured time-resolved IR absorption curve as shown

in Fig.10. The life time of the ground state electrons in the wells was determined to be greater than 40 ps as shown by the decay portion of the measured curve.

All of the absorption and PL measurements, and time-resolved IR absorption measurements in InGaAsP/InP MQW structures will be helpful to understand the basic physics and device performance in multi-band-gap InAs/InGaAs-InGaAs/InP-InP/InGaP MQW solar cells. In particular, the lifetime of the photoexcited hot electrons is an important parameter for the device operation of InGaAsP/InP MQW solar cells working in the resonant tunneling conditions.

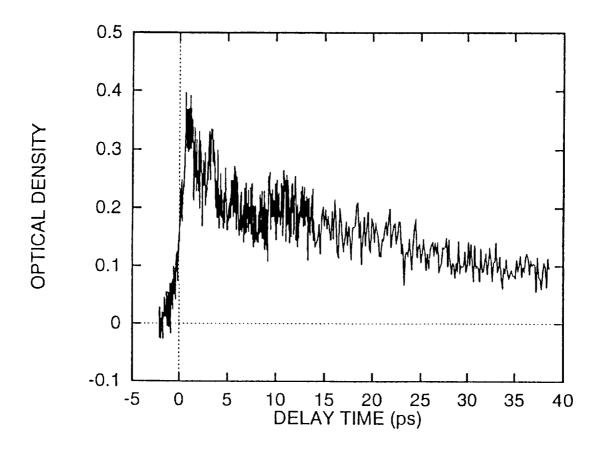


Fig.10. Time evolution of the hot carrier population in InGaAsP/InP MQW structures measured by femtosecond pump-probe IR absorption spectroscopy.

I.4. Temperature dependence of the time-evolution of hot electron population in GaAs

Time evolution of the hot electron relaxation in GaAs has been measured in the temperature range of 4 K through 288 K using femtosecond pump-IR-probe absorption technique. The temperature dependence of the hot electron relaxation time in the X valley has been measured. The measured temporal evolution of the IR probe absorption at 3.3 μ m at temperature of 4K, 77K, and

288 K are shown in Fig.11. The salient feature of the curves in Fig.12 is that as the temperature goes down the initial decay of the IR absorption increases. This decay time corresponds to the depopulation of the X_6 valley by intervalley scattering. This intervalley scattering is expected to slow down at low temperatures as has been observed. In addition, the change of the energy gap between the X_6 and X_7 valleys at their minima in GaAs as a function of temperature has been determined from the shift of the long wavelength threshold of the measured $X_6 \rightarrow X_7$ absorption—spectra at a fixed delay time as shown in Fig.12.

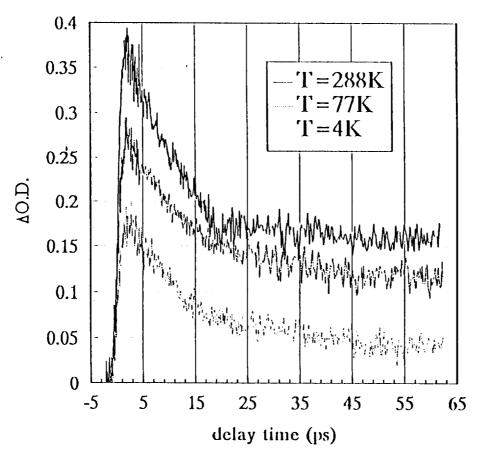


Fig.11. The measured temporal evolution of the IR absorption at 3.3 μm at temperatures of 4K, 77 K, and 288 K for GaAs.

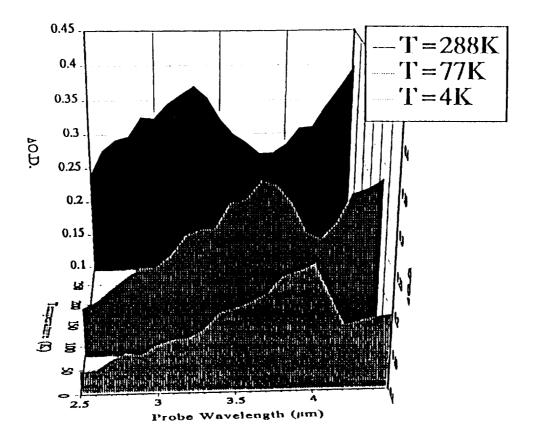


Fig.12. The measured shift of the long wavelength threshold of the $X_6 \rightarrow X_7$ absorption spectra in GaAs at 4K, 77K and 288K.

II. PUBLICATIONS, ABSTRACTS AND Ph.D THESES

A portion of our measurements and calculations has been published in scientific journals and conference proceedings.

The following lists the related publications and abstracts:

- 1. M. A. Cavicchia and R. R. Alfano, "Time-resolved IR-absorption spectroscopy of hotelectron dynamics in satellite and upper conduction band in GaP", Phys. Rev. <u>B51</u>, 9629 (1995).
- 2. J. M. Mohaidat, K. Shum, W. B. Wang and R. R. Alfano, "Barrier potential design criteria in multiple-quantum-well-based solar cell structures", J. Appl. Phys., <u>79</u>, 5533 (1994).
- 3. M. A. Cavicchia and R. R. Alfano, "Upper satellite conduction band population dynamics in GaAs measured by femtosecond UV pump-IR- probe absorption spectroscopy", OSA 1994 Technical Digest Series Vol.7, Ultrafast Phenomena IX, PP 128-130.
- 4. W. B. Wang and R. R. Alfano, "Femtosecond time-resolved infrared absorption in InP", Bull. Am. Phys. Soc., <u>39</u>, No.1, 221 (1994).
- 5. M. A. Cavicchia and R. R. Alfano, "Second conduction band relaxation of the photoexcited hot electron distribution in GaP", in the Advanced Program of the 1995 CLEO & QELS Conference (May 21-26, Baltimore), P 133.
- 6 J. M. Mohaidat, Kai Shum, W. B. Wang and R. R. Alfano, "Tunneling times and probabilities for multi-quantum well based solar cell structures", Bull. Am. Phys. Soc., <u>39</u>, No.1, 613 (1994).
- 7. M. A. Cavicchia and R. R. Alfano, "Femtosecond UV-pump and IR-probe absorption spectroscopy of energy relaxation in the X₆, primary, and X₇, second conduction band in GaP", Bull. Am. Phys. Soc., <u>39</u>, No.1, 545 (1994).

A number of other measurements and papers related to the research of Grant # NAG 3-1490 have been accepted for presenting in the "Ninth International Conference of Hot Carriers in Semiconductors" or will be completed for publications. These are:

- 1. W. B. Wang and R. R. Alfano, "Hot carrier dynamics in the X valley in Si and Ge measured by time-resolved visible-pump and IR-probe absorption spectroscopy", accepted for presenting in the "Ninth International Conference of Hot Carriers in Semiconductors".
- 2. O. Y. Raisky, W. B. Wang, R. R. Alfano, C. L. Reynolds, Jr. and V. Swaminathan, "Photoluminescence from above-barrier electron states in In_xGa_{1-x}As_yP_{1-y}/InP heterostructures", accepted for presenting in the "Ninth International Conference of Hot Carriers in Semiconductors".

- 3. M. A. Cavicchia, W. B. Wang and R. R. Alfano, "Intervalley scattering rate as a function of temperature in GaAs using time-resolved visible pump IR probe absorption spectroscopy", accepted for presenting in the "Ninth International Conference of Hot Carriers in Semiconductors".
- 4. W. B. Wang and R. R. Alfano, "Investigation of hot hole relaxation in InP measured by femtosecond pump-probe IR absorption spectroscopy", to be submitted for publications.
- 5. W. B. Wang, O. Y. Raisky, R. R. Alfano, C. L. Reynolds, Jr. and V. Swaminathan, "Hot carrier relaxation and recombination in InGaAsP/InP multiple quantum wells", to be submitted for publications.

During the past year, a Ph.D degree was awarded to J. M. Mohaidat under partial support of the grant # NAG 3-1490. The theses is entitled "Electron tunneling dynamics in engineered semiconductor nanostructures and applications to efficient solar cells". In the coming year, another Ph.D degree will most likely be awarded to M. A. Cavicchia (a U.S. citizen) under the support of the grant # NAG 3-1490.

III. CONTINUING RESEARCH PLAN FOR THE THIRD YEAR

During the third year, we plan to continue the calculations to design InP-based and GaAs-based multi-band-gap MQW solar cell structures, measure the absorption and PL spectra for the designed MQW structures, and investigate the energy conversion efficiency for these multi-band-gap MQW structures with resonant tunneling conditions. A comparison will be made with that for MQW structures with nonresonant tunneling condition and corresponding conventional single-band-gap bulk semiconductor solar cells such as InP and GaAs to obtain the best multi-band-gap MQW structures for high efficiency solar cells.

The following four research topics will be performed during the third year:

III.1. Design and preparation of the InP-based and GaAs-based MQW solar cell structures:

(a) Preparation of the GaAs-based InAs/InGaAs-InGaAs/GaAs-GaAs/AlGaAs MQW structures

Based on our designed multi-band-gap InAs/InGaAs-InGaAs/GaAs-GaAs/AlGaAs MQW structures, we will choose one of the basic units, for example, GaAs/AlGaAs MQW structures to test the resonant tunneling conditions and the enhancement of energy conversion efficiency for the multi-band-gap MQW solar cell structures. In order to compare with nonresonant and conventional solar cells, three kinds of samples will be fabricated: (1) the designed multi-band-gap InGaAs/GaAs MQW structures with resonant tunneling conditions; (2) the InGaAs/GaAs MQW structures with nonresonant tunneling conditions; and (3) the corresponding conventional single-band-gap bulk GaAs solar cells.

These three kinds of GaAs-based samples will be obtained from the Electronic Materials Laboratory at Grumman Corporate Research Center and/or the group for semiconductor nanostructure MBE growth in CCNY. The electric contacts will hopefully be made by these two groups to test the solar energy conversion efficiency.

(b) Design and preparation of the InP-based InAs/InGaAs-InGaAs/InP-InP/GaInP MQW structures

Based on our previous carrier dynamics and band structure measurements in InP, GaP, InGaP and InGaAsP/InP MQW structures, and the calculations on time-dependent short circuit current density as a function of barrier energy, we will continue to calculate the well-and-barrier parameters for an InP-based MQW structures consisting of three basic units: InAs/InGaAs, InGaAs/InP and InP/GaInP with resonant tunneling conditions.

One of these three basic units, for example, multi-band-gap InGaAs/InP MQW structures will be chosen to test the resonant tunneling conditions and the enhancement of the energy conversion efficiency. Three kinds of samples will be fabricated for comparison of the energy

efficiency: (1) the designed multi-band-gap InGaAs/InP MQW structures with resonant tunneling conditions; (2) the InGaAs/InP MQW structures with nonresonant tunneling conditions; and (3) the corresponding conventional single-band-gap bulk InP solar cells.

These three kinds of InP-based samples will be obtained from the Solid State Center of the AT&T Bell Labs. The electric contacts will hopefully be made by AT&T to test the solar energy conversion efficiency.

III.2. Spectral, hot carrier relaxation and energy conversion efficiency measurements in GaAs-based MQW structures:

(a) Absorption and PL measurements

Absorption and PL measurements will be performed for GaAs/AlGaAs MQW samples with resonant and nonresonant tunneling conditions to determine their structures and contributions of different layers of the samples to the measured absorption and PL spectra.

(b) Hot carrier relaxation time measurements

Energy relaxation of photogenerated hot carriers in GaAs/AlGaAs MQW structures will be measured by pump-IR-probe absorption or/and time-resolved PL spectroscopy using our femtosecond dye laser-and-amplifier system. The measured hot carrier relaxation time will be used to ensure that the resonant tunneling time is much faster than the electron-hole recombination time in the designed multi-band-gap MQW solar cells.

(c) I-V and energy conversion efficiency measurements

Current-voltage (I-V) characteristics in GaAs/AlGaAs MQW samples with resonant and nonresonant tunneling conditions, and in corresponding conventional single-band-gap bulk semiconductor solar cells will be investigated over appropriate spectral region using a black body light source and a monochromator. The measured I-V curve will be used to study resonant tunneling conditions and the enhancement of the energy conversion efficiency.

III.3. Spectral, hot carrier relaxation and energy conversion efficiency measurements in InP-based MQW structures

(a) Investigation of above-barrier resonant state for InGaAsP/InP MQW

We have designed three InGaAsP/InP MQW structures with same well width but different barrier width (70A/70 A, 70A/100A and 70A/150A), which have been fabricated in AT&T Labs in Breinigsvill. We are meausring absorption and PL spectra for these new samples to further study the above-barrier electron resonant states and their effect to the collect current density for InGaAsP/InP MQW based solar cells.

(b) Absorption and PL measurements

Absorption and PL measurements will be performed for InGaAs/InP MQW samples with resonant and nonresonant tunneling conditions to determine their structures and contributions of different layers of the samples to the measured absorption and PL spectra.

(c) Hot carrier relaxation time measurements

Energy relaxation of photogenerated hot carriers in InGaAs/InP MQW structures will be measured by pump-IR-probe absorption or/and time-resolved PL spectroscopy using our femtosecond laser system. The measured hot carrier relaxation time will be used to ensure that the resonant tunneling time is much faster than the electron-hole recombination time in the designed multi-band-gap MQW solar cells.

(d) I-V and energy conversion efficiency measurements

Current-voltage (I-V) characteristics in InGaAs/InP MQW samples with resonant and nonresonant tunneling conditions, and in corresponding conventional single-band-gap bulk semiconductor solar cells will be investigated over appropriate spectral region using a black body light source and a monochromator. The measured I-V curve will be used to study resonant tunneling conditions and the enhancement of the energy conversion efficiency.

III.4. Modeling and analyzing the prior results for publications

We will continue to model and analyze the absorption and PL experimental results, femtosecond pump-IR-probe absorption measurements for InGaAsP/InP bulk and MQW structures, and hot carrier dynamics measurements for GaAs described in Sections I.2, I.3 and I.4, and will complete corresponding papers for publication.